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EVALUATION OF THE UTILITY OF A LARGE-SPACING DIPOLE-DIPOLE BOREHOLE LOGGING TOOL

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April 1, 1985

Lawrence Livermore National Laboratory

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EVALUATION OF THE UTILITY OF A LARGE-SPACING DIPOLE-DIPOLE BOREHOLE LOGGING TOOL

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I. Introduction

The importance of detecting montmorillonite clay zones in the vicinity of the working point of an underground nuclear test was inferred by post-shot studies of the Baneberry event. Montmorillonite has relatively low shear strength, especially when wet, and its presence can result in zones of mechanical weakness. Current practice by the Containment Evaluation Panel (CEP) is to avoid areas with montmorillonite content of more than 30% over an appreciable depth range (Olsen, 1983).

At this time there is no way to accurately predict the location of montmorillonite clay zones. Their physical properties make them difficult to detect with seismic or gravimetric techniques. Clay zones are generally associated with areas where tuff deposits have been altered by groundwater associated with fault zones, but are not confined to such areas. Area 8 at the Nevada Test Site (NTS) probably contains the most extensive occurrence of clay zones in the subsurface. Locations of the clay zones can only be detected with certainty by drilling, sampling, and subsequent x-ray analysis. Development of a method to remotely sense the location of these clay zones will greatly aid in the process of emplacement hole siting as well as in the even more important area of containment evaluation for a given emplacement hole.

The low electrical resistivity of zones associated with high clay content contrasts with the tuff and alluvium in which they are found. Experience has shown that clay zones are generally associated with sections of borehole electric logs where resistivities are lower than 100 ohm-m. (Zeolite can also be present in this low resistivity signature, but this separate problem will not be addressed here.) The limitation of standard electric logging methods is that they only sample to a depth of a few meters from the borehole. A method is therefore needed which will extend the sensitivity to the presence of zones of low resistivity from a few meters away out to distances greater than one cavity radius away from the emplacement point.

Previous work, discussed below, has revealed that surface electrical surveys cannot detect deep anomalies with sufficient resolution to be of use. We are thus left with the consideration of downhole electric methods. Such methods will require considerable technical effort to develop a borehole tool. This paper is a report of a theoretical analysis of the potential of downhole dipole-dipole measurements. We first analyze simple geometries and then evaluate various interpretation schemes based on simulation of field measurements. Finally, an assessment of the value of the proposed borehole tool is made in terms of usefulness to containment evaluation.

II. Previous Studies and Plan of Investigation

A. Previous Studies

Previous theoretical work by personnel at LLNL have included studies of surface electrical surveys and various surface-to-borehole methods. These methods were considered in the context of applying available technology to an exploration scheme without expending resources in extensive research and development. Each technique has problems which make it unacceptable for solving the clay detection problem.

The main problem with surface methods (where the current source and voltage receiver are both located at the surface) is that resolution of the character (shape, resistivity contrast) of a resistivity anomaly is inversely proportional to the depth to the anomaly. Deep anomalies are difficult to detect and resolve. Working point depths of concern are typically 300 m and as deep as 450 m or more. Examples of the problems with detection of such anomalies are shown in Fig. 1.

Figure 1 shows an ideal situation where a 50 m thick clay slab, with a resistivity of 5 ohm-m, is surrounded by tuff or alluvium with a resistivity of 100 ohm-m. In Fig. 1a the slab is 350 m wide, of infinite length in and out of the figure, with the top of the slab 50 m below the surface. In Fig. 1b the slab is similar in shape but 150 m deep and it is 35 m wider. These are reasonable geometries to represent a clay zone at depth, except that these are somewhat shallower than would be of concern for containment applications.

The results shown in Fig. 1 are for a model calculation assuming the surface galvanic resistivity technique used is a dipole-dipole survey. However, the results would be qualitatively similar for the Wenner or Schlumberger electrical depth sounding methods which are also used in exploration geophysics. The dipole-dipole method (see Fig. 2) is carried out by injecting current into the ground between two electrodes (the transmitter) separated by the dipole length, a. Voltage is then measured between two electrodes (the receiver) separated by dipole length a. The two sets of dipoles are separated by some integral number of a dipole length, designated as na, where n = 1,2,3,...etc. The dipoles are in a line which is generally chosen to be perpendicular to the strike of the subsurface resistivity structure. For a given spacing of the dipoles (n-spacing) an apparent resistivity is found by dividing the measured voltage by the amount of current injected and multiplying by a geometric factor (see Keller and Frischknecht, 1966). The apparent resistivity represents a bulk averaging of the true subsurface resistivity along some volume (dependent upon subsurface

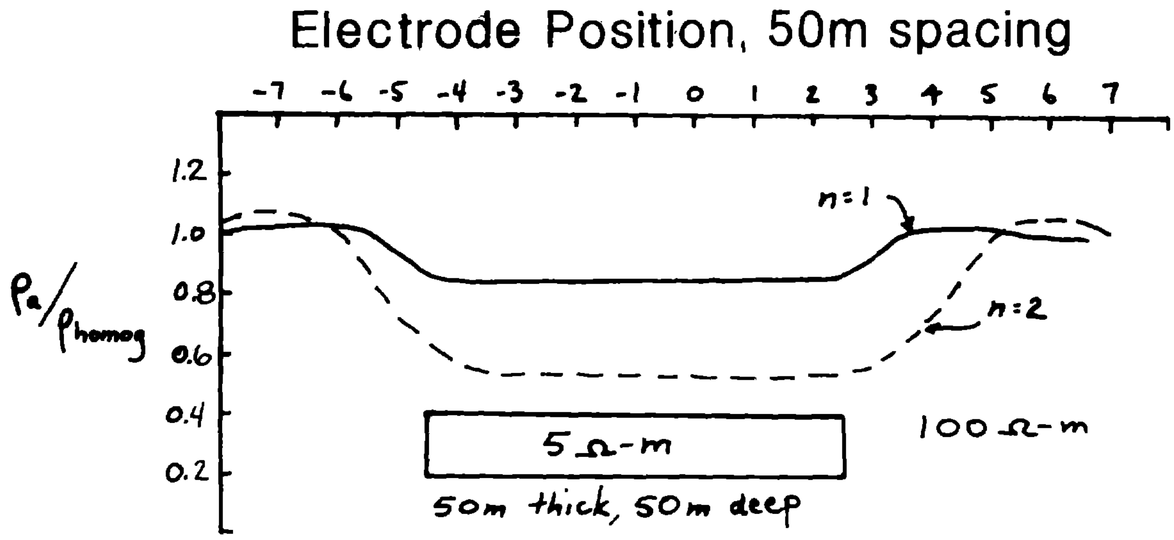

Figure 1a. Dipole-dipole resistivity profile (using the measurement geometry of Figure 2) calculated for a 100 ohm-m matrix with a 5 ohm-m buried slab anomaly. The survey line is run perpendicular to the axis of the slab. The calculated apparent resistivity is normalized to the apparent resistivity of a homogeneous background.

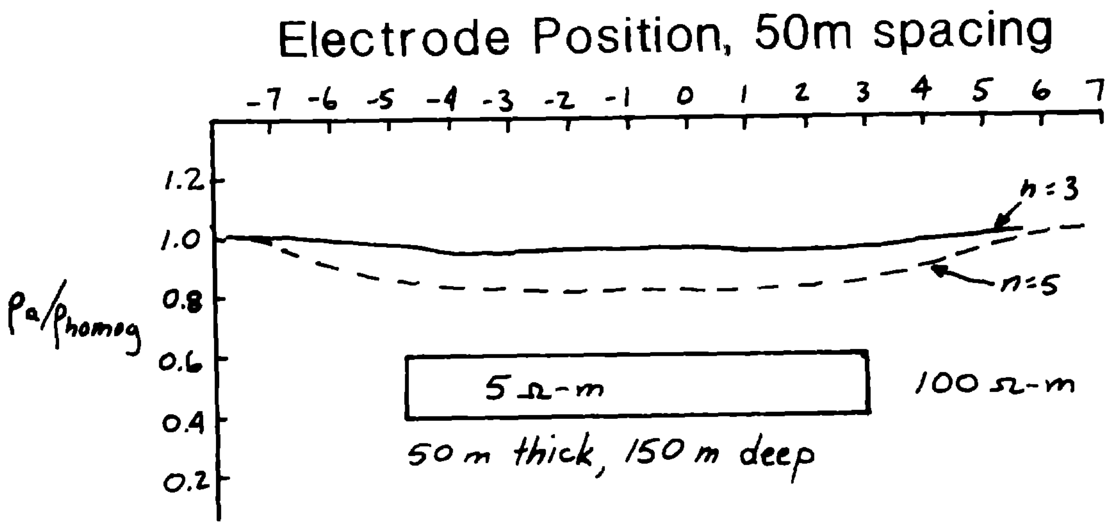

Figure 1b. Profile like that of Fig. 1a with the slab buried three times deeper.

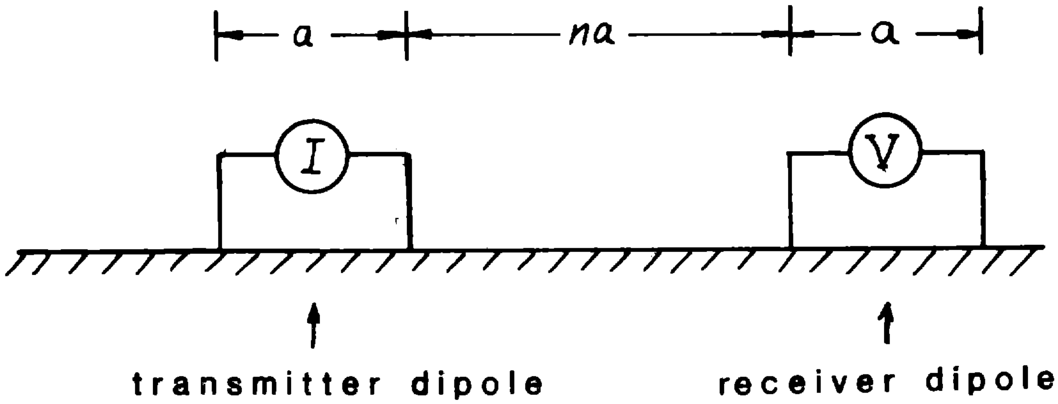

Figure 2. Geometry of the colinear dipole-dipole resistivity measurement at the earth's surface.

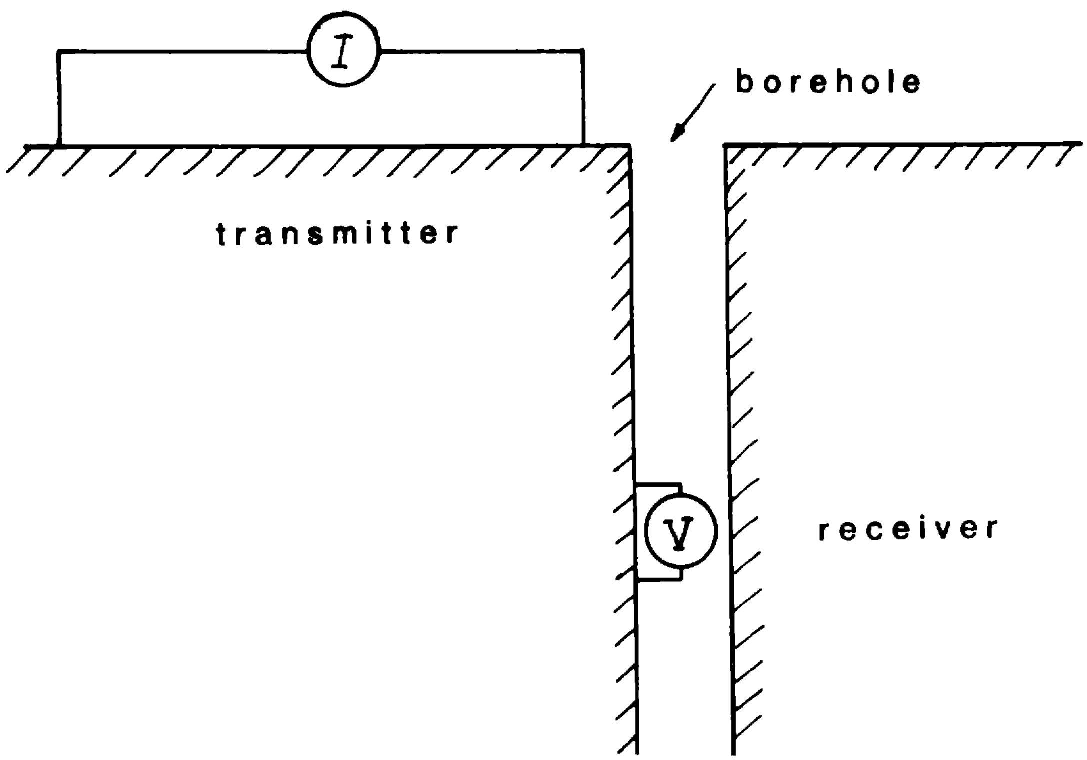

Figure 3. Geometry of a surface-to-borehole resistivity measurement.

resistivity structure) between the transmitter and receiver dipoles. Short dipole spacings (low values of n) sample the area near the surface, long dipole spacings (large n values) sample deeper. A rule of thumb, which holds for n less than 6, is that a dipole spacing of na samples to a depth of 1/2 na.

The profiles of Fig. 1 were calculated using the resistivity code developed by Dey-Morrison (1976). The code calculates the profile of apparent resistivity for the half-space situation with an arbitrary resistivity structure extending infinitely below and in the direction perpendicular to the survey line. Values of apparent resistivity are calculated for n-spacings up to n = 15, but in practice reliable measurements can usually be obtained only out to n = 4 to 6.

In Fig. 1, the apparent resistivity profile in each case has been divided by the case for a homogeneous subsurface so that the relative effect of the anomaly can be readily seen. For the shallower anomaly, Fig. 1a, a 16% decrease in apparent resistivity over the anomaly is seen for n = 1, with a 46% decrease for n = 2. Our experience in the field is that a 10-15% variability due to geologic variability and surface effects is typical of the background "noise", thus the clay zone of Fig. 1a should be readily detectable. The deeper anomaly shown in Fig. 1b shows only a 4% change at n = 3 and an 18% change at n = 5 - this clay zone would be close to the limit of detectability. A rough estimate of the lateral resolution of such an anomaly is probably of the order of a dipole spacing, or 50 m in this case.

From the results shown in Fig. 1, it is apparent that dipole lengths on the order of 200 m or more will be needed to detect clay zones at depths of 300 to 400 m with a surface survey. The zone would have to be a half dipole length or more thick (100 m or so) to be detected with certainty and the lateral resolution of its extent would be on the order of 100 m or worse.

Because containment requirements need lateral resolutions on the order of 10-20 m, these results show that surface surveys will not be adequate for the needs of containment evaluation.

The possibility of using a geometry in which a current source is placed at the surface and voltage is measured in a borehole was investigated (as shown in Fig. 3). This is called the surface-to-borehole method (see Daniels, 1977). This technique has the advantage that the detector, which is placed in the borehole, is closer to the anomaly. The only type of detector presently usable in the large diameter dry emplacement holes at Yucca Flat at the NTS is the receiver dipole of the big-hole-dry-hole (BHDH) electric logging tool. This has a maximum dipole length of 3 m. Calculations for this geometry, assuming an ideal case such as that of Fig. 1, were carried out using a code developed by Lytle and Hanson (1983). The results of the investigation showed that the short spacing of the receiver dipole length was a major disadvantage for anomalies located distances greater than 50 m from the borehole. A further disadvantage with this geometry is that very high current at the surface is required to obtain a good signal-to-noise ratio at the receiver. Results using this geometry would be vastly improved, however, if a means would be devised to obtain a larger (20 m or greater) dipole length for the downhole receiver dipole.

Two other methods were also considered. The mise-a-la-masse method involves placing the current source in a borehole at a zone of low resistivity and mapping the surface potential distribution to delineate the shape of the source mass. Another method considered was to lower radio frequency (r.f.) current loops into the hole to use as a source and receiver. At present, we have no way of modeling these geometries and interpretation may be difficult. For the above reasons, these methods were also deemed inappropriate for the immediate needs of containment evaluation.

B. The Proposed Investigation

If one were to consider a situation in which the actual technical means of carrying out an electrical measurement were not of concern, but a method of modeling and analysis were readily available, a downhole dipole-dipole technique would be an excellent choice for detecting clay bodies in the borehole vicinity. A downhole dipole-dipole survey would involve the placement of electrode pairs of arbitrary dipole length, separated by n = 1 to 3 or 4, into a borehole for continuous recording of potential. With this geometry, a borehole measurement would be analogous to a surface measurement in which the horizontal layers in the surface case are modeled as vertical layers in the borehole case.

When modeling a downhole dipole-dipole resistivity survey, two assumptions must be made. The first is that the borehole does not significantly affect the current radiation pattern. This assumption is well justified when the distance from the source dipole to the measurement dipole is greater than five times the borehole diameter (Lytle, 1984). The second assumption is that the whole-space can be modeled using a half-space solution of the potential equations. This assumption is not strictly applicable in this case, but can be worked around. It is evaluated further in the following section. With these assumptions, the surface resistivity modeling code of Dey-Morrison (1976) has been used to model the borehole geometry.

In order to actually carry out downhole measurements in a large diameter dry hole, some means will have to be devised to clamp electrodes in the borehole at the proper spacing. The electronics for the direct-current transmitter and receiver are of no real concern, as adequate equipment is already available. Development of the big-hole dry-hole electrode system, however, could require a large development effort. Before considering a large expenditure of resources it is prudent to fully examine the results to be expected from a downhole dipole-dipole measurement scheme. This is the main purpose of this report.

The first step in the feasibility study is to look at simple earth geometries, similar to those of Fig. 1, to see how well the dipole-dipole method works in the most ideal case. Later, we show the results of more complicated modeling in an attempt to predict as well as possible the actual conditions to be expected in the field.

III. Modeling of Simple Geometries

A. Model Geometries and Evaluation of the Half-space Assumption

To quantify the response of a dipole-dipole downhole tool for a case in which an anomalous low resistivity zone occurs near but not intersecting the borehole, a series of simple cases were modeled using the Dey-Morrison code, called RESIS2D. The cases modeled consist of anomalously low zones of resistivity surrounded by a homogeneous matrix. Geometries used were layers of different thickness, a wedge, and a prism. Resistivity contrast and distance of the anomaly from the borehole were also varied. All results are given relative to the response of the survey in a homogeneous medium and relative to a dipole unit length, a. This allows one to better see the effect an anomaly produces uncomplicated by absolute units. With the unit of length fixed as the dipole spacing, the results are generalized to an arbitrary scale.

The Dey-Morrison code is a solution for a half-space geometry. In the whole-space (down the borehole) situation current radiates in all directions from the transmitting dipole. The effect of a nearby low resistivity anomaly is to concentrate current and perturb the current and potential fields. In the half-space case (surface measurement) current is confined to the lower half-space and the perturbation of the fields due to the presence of a low resistivity anomaly is greater than in the whole-space case. Therefore, changes in the apparent resistivity, relative to a homogeneous earth, will be more pronounced in the half-space geometry. The quantitative difference between the two cases is difficult to determine analytically because it depends on the resistivity contrast, geometry of the anomaly, and geometry of the electrodes. We can, however, estimate the difference by using a feature of the Dey-Morrison code which allows the survey line to be moved downward (Z-shifted) by an integral number of dipole unit lengths.

If, in the half-space model, the survey line is shifted downward so that the survey line is "buried" several dipole lengths below the surface, the calculation will approximate a whole-space solution for a few n-spacings away from the survey line. In the model, a vertical dike of low resistivity located below the survey line will serve to represent a horizontal anomaly located to one side of a borehole (the horizontal survey line here represents the vertical borehole location).

The half-space model (no Z-shift) and the whole-space approximation (Z-shift = 3a) are compared in Figure 4. In each case, the anomaly has a resistivity contrast of 1:20 with the surrounding medium, a thickness of one dipole length, and is located 1/2, 1, and 3 dipole lengths away from the borehole. The calculated apparent resistivity relative to a homogeneous matrix is plotted versus depth in units of dipole length. Figure 4a is the half-space model and Figure 4b is the whole-space approximation.

The curves for the whole-space model (4b) have lower amplitudes than corresponding curves in the half-space model (4a), but the shapes of the curves are quite similar. This is because of the current-concentrating effect described above. Curve amplitudes for the whole-space case range from 56% (n=1) to 71% (n=2) of those of the half-space case when the anomaly is 1/2a away. This means that when half-space models are used to compare effects of different low resistivity anomaly geometries, the resulting curves are exaggerating the real case by a factor of 1.4 to 1.7. The difference will be less for anomalies farther from the hole and for greater n-spacings because of the weakening of current density away from the source.

A comparison like Figure 4 is done in Figure 5 for the case where the resistivity contrast is 1:5. Differences in the two sets of curves are about the same as for Figure 4. Only the amplitudes of the curves are different in each case. Because of this, the half-space model can be used in studies related to the effects of model geometries on the shapes of the curves, as is done below.

The Dey-Morrison code is designed for the half-space geometry, and thus is most accurate when used in that mode. Calculations with a Z-shift are only approximations to a true half-space geometry. Because of this, we have chosen to use the Dey-Morrison code in the original (Z-shift=0) half-space mode for studying the effects of various resisitivity anomaly geometries with the caveat that amplitudes of the calculated curves will be exaggerated by a factor of 1.5 to 1.75 over real-earth results. These differences in the models have been factored into the final analysis and evaluation.

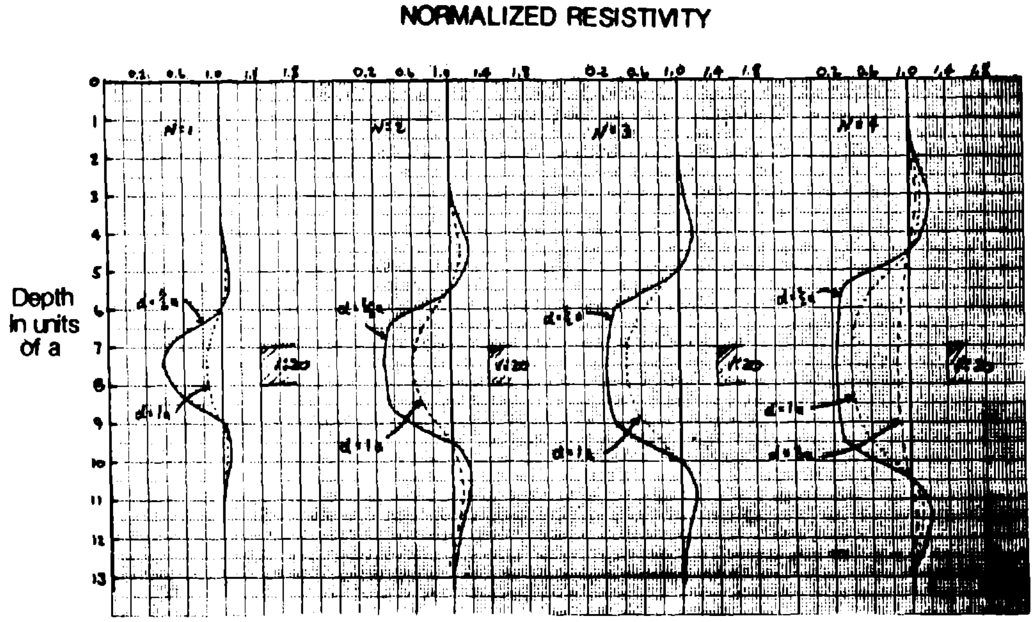

Figure 4a. Half-space solution (Z-shift=0) of normalized apparent resistivity for an anomaly with resistivity contrast of 1:20. Anomaly is one dipole spacing thick.

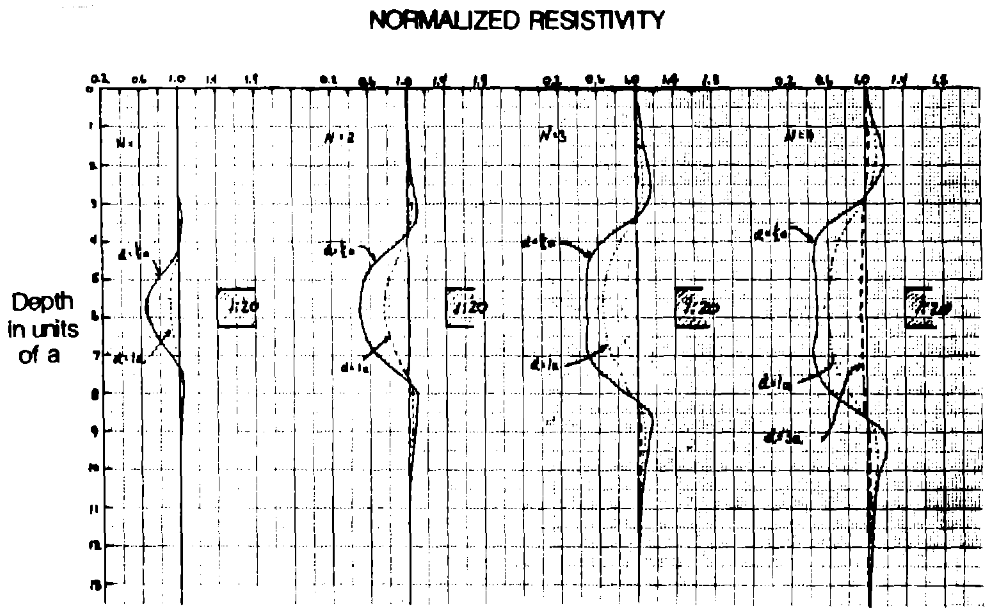

Figure 4b. Whole-space approximate solution (Z-shift=3) for same case as Fig. 4a.

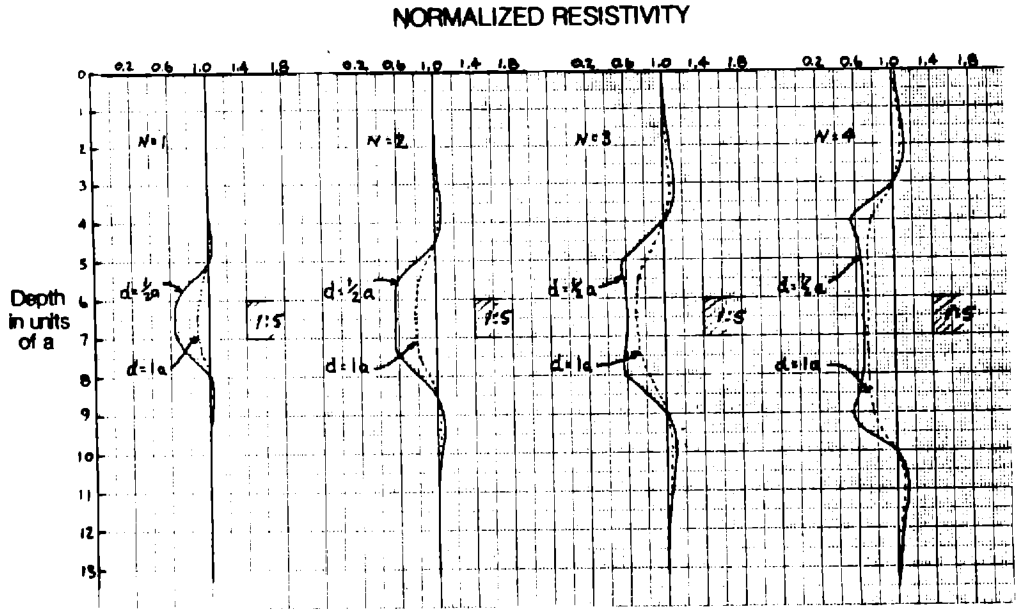

Figure 5a. Half-space solution (Z-shift=0) of normalized apparent resistivity for an anomaly with resistivity contrast of 1:5. Anomaly is one dipole spacing thick.

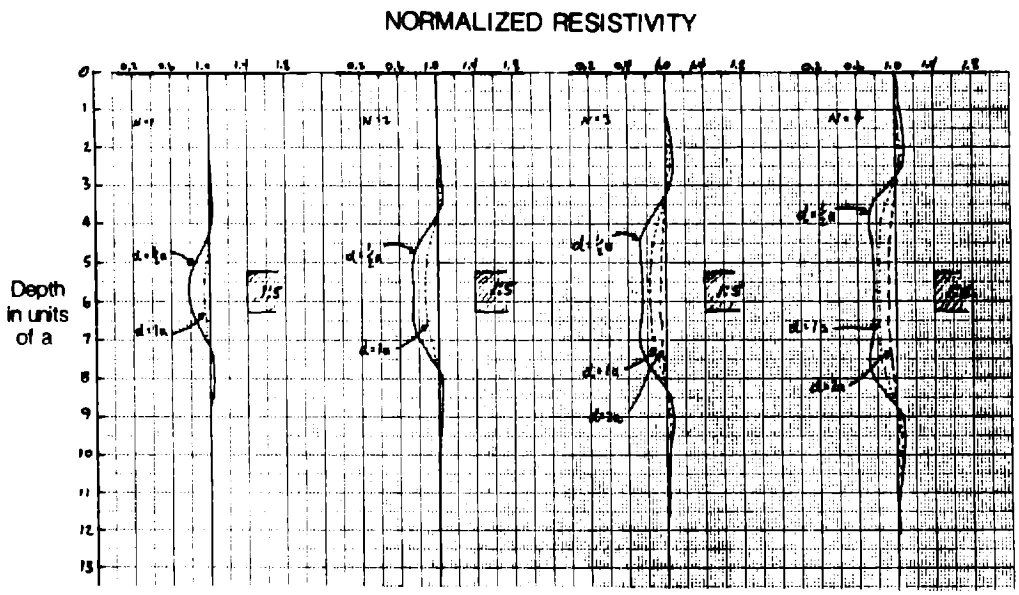

Figure 5b. Whole-space approximate solution (Z-shift=3) for same case as Fig. 5a.

B. Results for Geometric Models

For each model run, five borehole-log type graphs have been plotted (Figures 4-8) corresponding to an n-spacing varying from one to five. Each curve is the ratio of the solution for a survey with the anomaly present to the solution for a survey with no anomaly present. For a given n value the distance of the anomaly from the borehole in units of dipole length is indicated.

Figure 4 shows the effect produced by a layered anomaly one dipole unit thick. The anomaly has a resistivity one twentieth that of the surrounding medium (1:20 contrast), which is a likely contrast when encountering a clay layer in tuff. The results show a broadening over the anomaly as n is increased. This is expected since a larger n means the source dipole and receiver dipole are further apart, probing farther away from the borehole wall, and hence influenced by the anomaly over a larger vertical region. For any given n spacing, the amplitude of the response due to the anomaly is lower if the anomaly is farther away, but the vertical extent of the response is unchanged. For example, for n = 4 the 1/2, 1 and 3 dipole spacing curves are respectively lower in amplitude, yet the general shape and crossover points on the vertical axis remain unchanged.

Another important feature of Fig. 4 is that for a given curve the anomaly amplitude reaches a maximum at a certain n value. For example, for the curve of Figure 4a where the anomaly is 1a away, the value of the peak is 0.82, 0.58, 0.43, 0.40, 0.40 for n=1,2,3,4,5 respectively (n=5 not shown). Thus, n=2 represents a threshold value for the amplitude of the anomaly curve. This threshold n-value is dependent on the distance of the anomaly from the borehole. Figure 4 also shows all the curves to be symmetric about the anomaly. This is to be expected because of the symmetry of the anomaly.

Figure 5 is the case for a layered model like Fig. 4, but the anomaly resistivity contrast is 1:5 instead of 1:20. Except for the crater-like depression in the response curve occurring over the anomaly for higher n-values and the sharp reduction in the anomaly amplitudes, the curves are very similar to that of Figure 4. Crossover points and the n value which gives maximum amplitude are unchanged with contrast.

The results shown in Fig. 6 are for a layered model in which the anomaly thickness is two dipole lengths. The curves, when compared to those of Figure 4, are broader for each n value by exactly one dipole length. As seen in Figure 4, the crossover points are not affected by the distance to the anomaly and the threshold n-value remains unchanged. The amplitude of the anomaly is significantly larger than that of Fig. 4 and the curves for higher n values take on the crater-like shape over the anomaly as in Fig. 5. Were it not for the broadening of the curves as the anomaly thickness increases, one would not be able to distinguish between different thicknesses and contrasts.

Two other anomaly shapes were modeled, both at a spacing of 1/2 dipole length from the borehole. Figure 7 is the case for a wedge, tapering to zero from a thickness of 4a at a 45 degree angle. The curves are asymmetric with an upper weak crossover and a larger lower one. The approximate centroids of the curves for small n-values coincide with the bottom of the wedge. This could give an erroneous indication of depth if one interpreted the data without using the higher n-value curves. The fact that the small n-value curves center about the tip of the wedge is expected, because for lower n-values the current will not penetrate much beyond the tip of the wedge. Hence, the anomaly above is not detected. Figure 8 is the case for a triangular anomaly. This case is very similar to Figure 7 for low n-values,

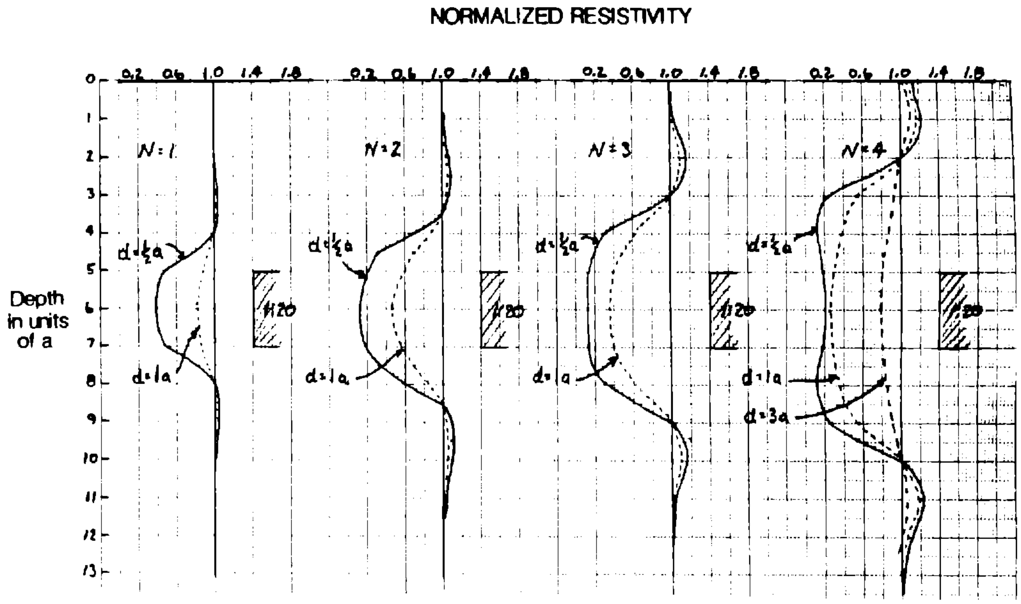

Figure 6. Half-space solution (Z-shift=0) of normalized apparent resistivity for an anomaly 2a thick with a resisitivity contrast of 1:20.

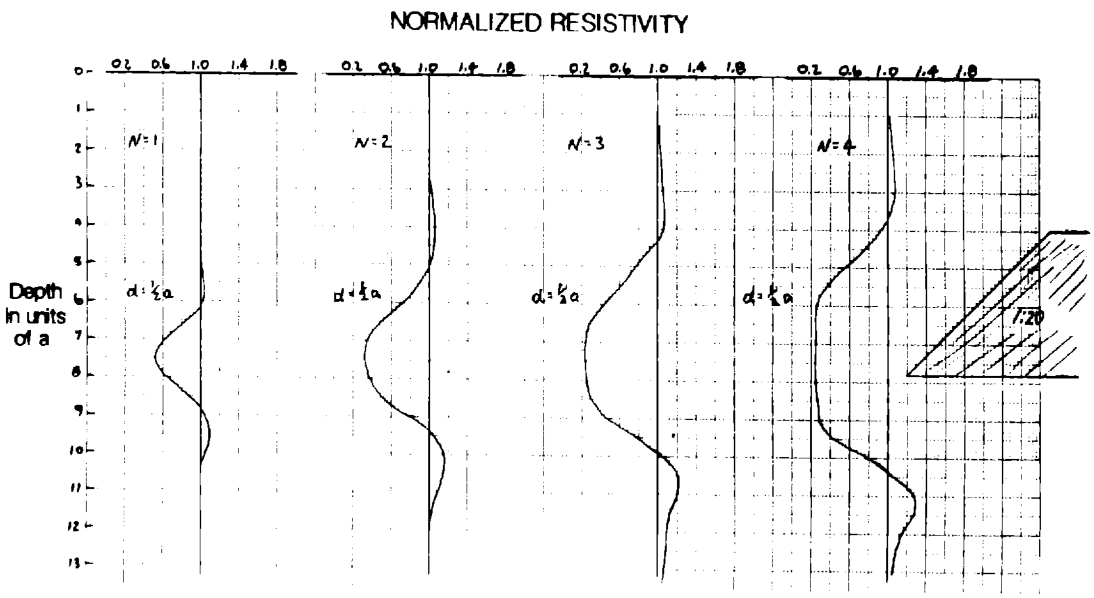

Figure 7. Half-space solution (Z-shift=0) of normalized apparent resistivity for a wedge anomaly tapering from a thickness of 4a. Resistivity contrast is 1:20.

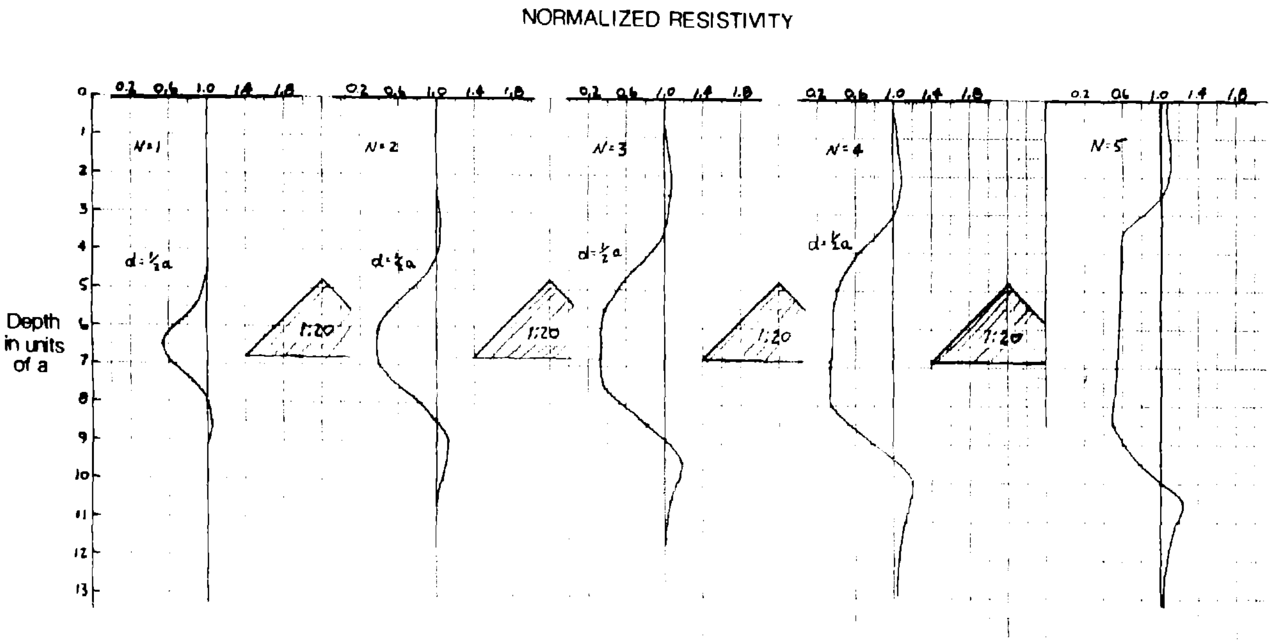

Figure 8. Half-space solution (Z-shift=0) of normalized apparent resistivity for a triangular anomaly with a 1:20 resistivity contrast.

when the depth of penetration of the current is not great. For n = 5, however, we see a marked reduction in anomaly amplitude. This indicates that the current has now "seen" the far terminating edge of the anomaly. Thus, reductions of amplitude at larger n-values can be a good indicator that the anomaly is "pinching out" away from the borehole.

C. Summary

These ideal case anomalies suggest an interpretation procedure for the case of layered or layer-like earth anomalies. The primary concern, most important to NTS applications, is to determine the distance of the anomaly from the borehole. This can be accomplished by running surveys at several n-spacings and comparing the resulting curves. The lowest n-value at which the anomaly reaches its maximum amplitude indicates the distance to the edge of the anomaly. As seen in Figs. 4 to 8, if this occurs at n = 1, the anomaly is half a dipole length or less away. For n = 2, the anomaly is closer to 1 dipole away. An anomaly detected only at n = 4 or 5 would be on the order of three dipole lengths away from the borehole.

The anomaly thickness can be estimated by comparing the vertical distance between the curve crossover points. A thicker layer will have a greater distance between the anomaly crossover points for a given n-value. Comparison of this distance to the ideal curves will allow a thickness estimate.

Anomaly resistivity contrast, as shown in Figs. 4 and 5, primarily affects the amplitude of the survey curve. Consequently, after the thickness is determined, comparison of the amplitude to those of the ideal curves will result in an estimate of the resistivity contrast.

Finally, the vertical location of the anomaly is easily obtained by locating the central peak of the survey curve. This depth should correspond to the center of the anomaly.

It should be noted that the above determinations can only give estimates of the depth, distance, and resistivity contrast of an anomaly with respect to the borehole and its surrounding media. Because of symmetry considerations, the azimuthal location of an anomaly with respect to the borehole cannot be determined with this method.

IV. Simulations of real borehole data

In the real world, the subsurface resistivity structure is not as simple as in the models studied above. Study of the simple models suggests methods of interpreting borehole data, but it does not provide insight into limitations on the analysis of real data. In order to gain insight into the problem, we decided to run simulated models of real data using the Dey-Morrison code in the half-space mode (Z-shift=0).

Two types of scenarios can be envisioned where data has been obtained with a downhole dipole-dipole logging tool. In one case, only the dipole-dipole logs at two spacings, say $n = 1$ and $n = 3$, are available. In another case, the dipole-dipole log data would be complemented by the availability of the electric log for the borehole. The advantage of the electric log data, which is sensitive to resistivity of materials within only a few meters of the borehole, is that it gives an approximation of the $n = 1$ spacing results to be expected with the dipole-dipole tool. By comparing the $n = 1$ and $n = 3$ spacing data with results from the electric log, one can get an indication of whether any anomalies are located more than a few meters away from the borehole.

An example of case two above is seen by an analysis of simulated results from borehole U2CQ. The BHDH log of U2CQ is shown in Fig. 9 along with the borehole model used to simulate the data. The assumption used here is that the BHDH log represents a true picture of the subsurface resistivity structure along the borehole. The model was used in the RESIS2D code to generate curves of apparent resistivity versus depth for various n-spacings. Curves for the n = 1 and n = 3 spacings are shown in Fig. 10a. These curves represent the (noise free) response of a dipole-dipole tool, with a dipole length of 50 ft. (15m.), for the model structure of Fig. 9b. Note that the n = 1 curve of Fig. 10a is a "smoothed" version of the BHDH log of Fig. 9a.

In order to assess the response of the dipole-dipole tool to the presence of a zone low resistivity (representing a clay zone), the model of Fig. 9b was used with the inclusion of a 5 ohm-m anomaly. The simulated anomaly was a 50 ft. (15m.) thick infinite slab with closest approach 50 ft. away (one dipole length) from the borehole. Placed at a depth of 925-975 ft. with a resistivity of 5 ohm-m, the anomaly had a resistivity contrast of 1:4 with the surrounding 20 ohm-m material. The calculated response for the structure with the anomaly included is shown in Fig. 10b.

The curves for the n = 1 spacing are, for practical purposes, identical. The only effect of the anomaly is seen on the n = 3 curve as a slightly lower amplitude between 925 and 975 ft. From the model shown in Fig. 4, we know that an anomaly one dipole length away from the borehole will not affect the n = 1 curve, but will show up on the n = 3 curve.

In actual practice, Fig. 10b would represent the results from a field deployment of a dipole-dipole tool (exaggerated due to the half-space effect, as discussed above). Fig. 10a would represent a model based on interpretation

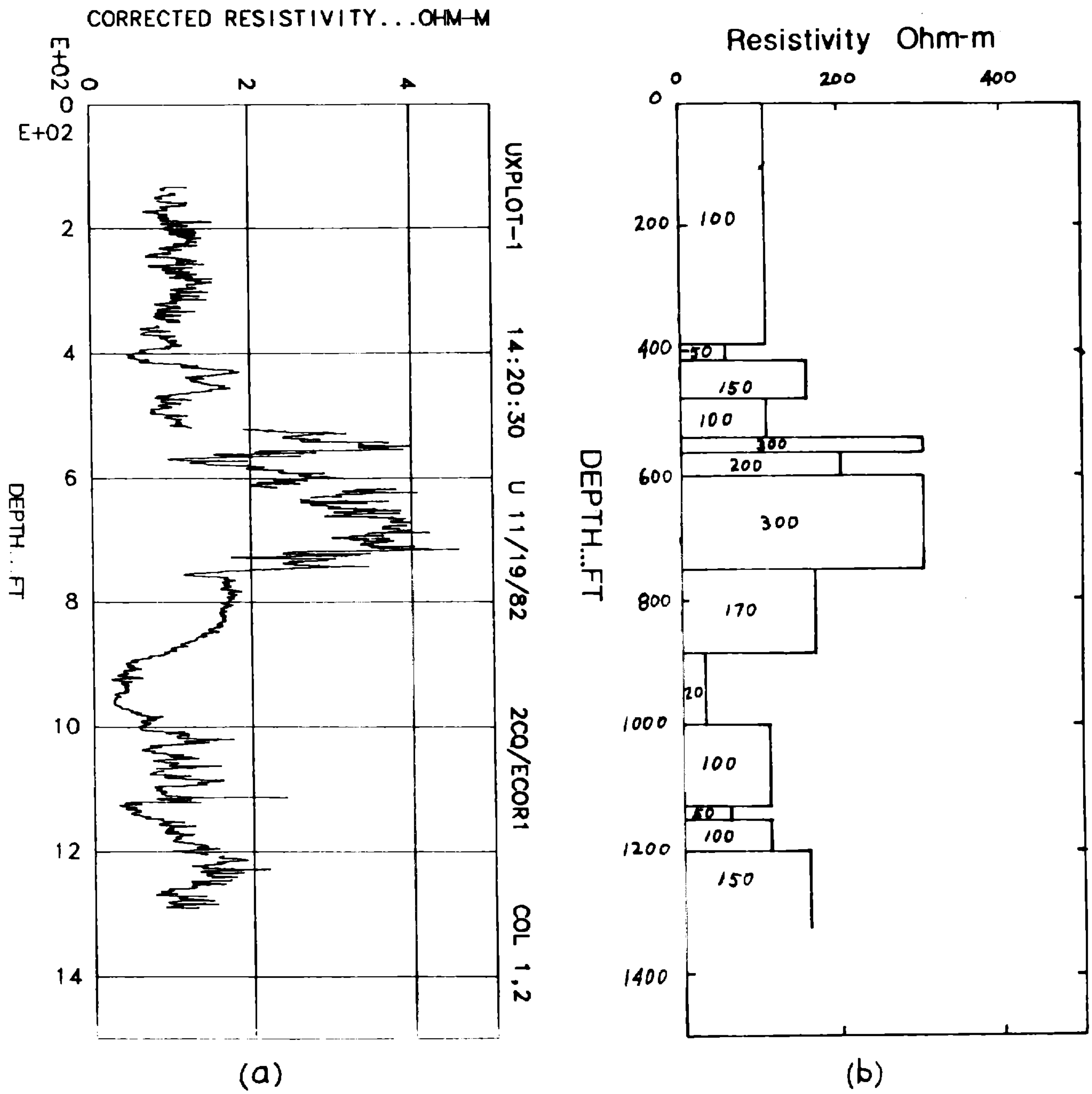

Figure 9.(a) BHDH log of borehole U2CQ. (b) Resistivity structure used to model the response of a dipole-dipole tool used in U2CQ.

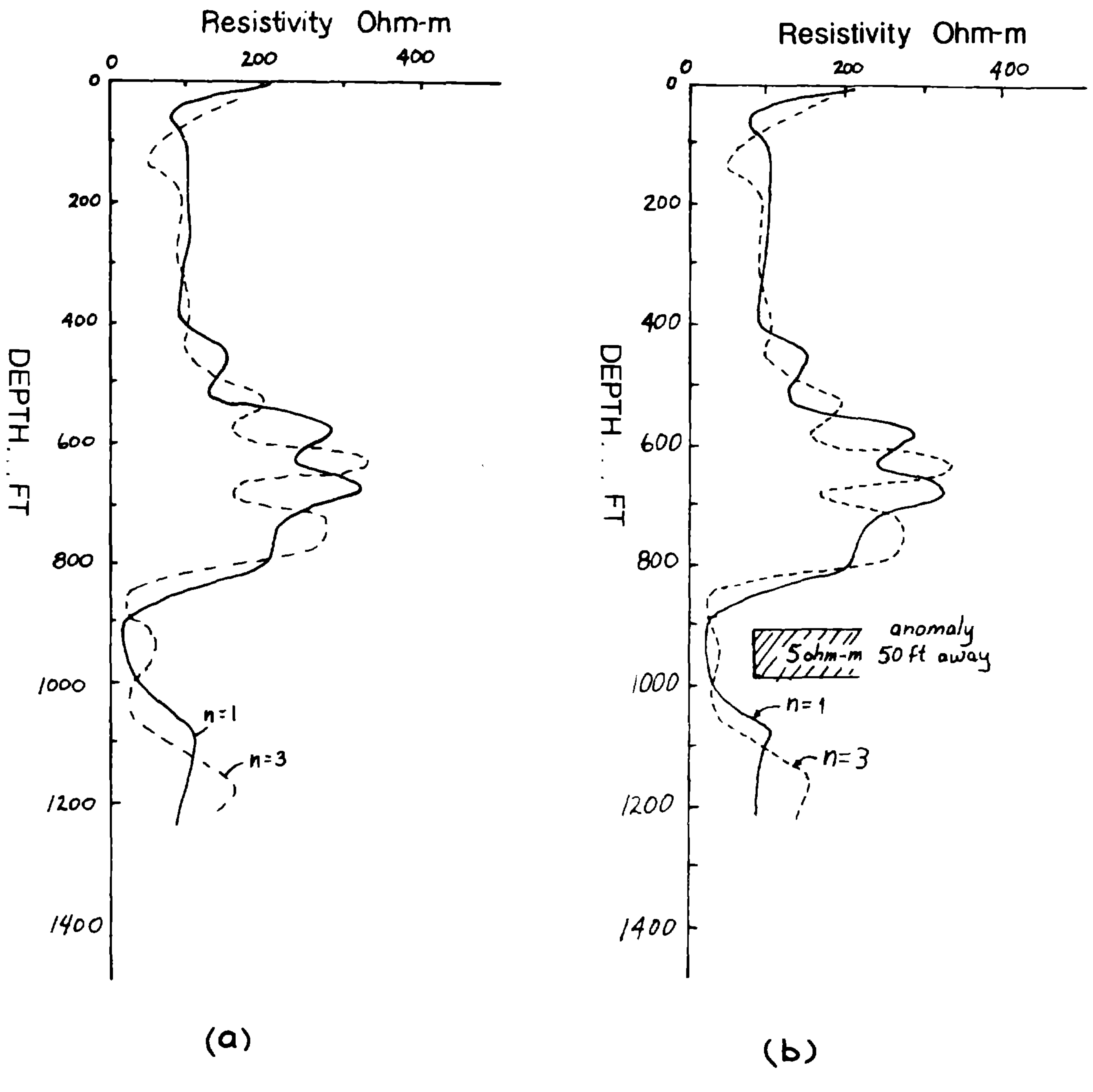

Figure 10. (a) Calculated dipole-dipole response, a=50ft (15m), for the structure of Fig. 9b. (b) Calculated response, a=50 ft, for the same structure as 9b, with a 50ft thick 5 ohm-m anomaly 50 ft away from the borehole between depths of 925-975 ft.

of the BHDH log. The ratio of the Fig. 10b curve to the 10a curve, shown in Fig. 11, reveals a signature of the anomaly more like those seen for the simple models. In this case, we have "filtered out" the background response and are looking at the difference between remote (Fig. 10b) and nearby (Fig. 10a) probes of the borehole vicinity. The curve of Fig. 11 is best compared with the curves of Fig. 5a (1:5 contrast, one dipole length spacing from the borehole).

We know that the electric log curve is not a perfect representation of the near-borehole resistivity structure. The curve contains noise due to instrument and tool response, inhomogeneities near the borehole wall, and so on. Furthermore, we do not know if a proposed dipole-dipole tool will have an n = 1 response curve anything like the curve seen by the electric log. Thus, a certain amount of uncertainty is involved when the electric log response is used as a background level reference when looking for anomalies.

One way to look at the effect of uncertainty in the background curve is to compare different simulated curves obtained from a given BHDH log. Figure 12 shows the BHDH log for borehole U4ac with two different resistivity structures superimposed. Model 12a is a fine structure with 17 separate layers. Model 12b is a coarse structure with only 5 layers. The RESIS2D code was used to calculate the dipole-dipole response for these structures with 75 ft dipole lengths. In Fig. 13, the percentage difference between the two curves versus depth is plotted. The horizontal scale consists of:

$$\frac{\text{fine value - coarse value}}{\text{coarse value}} \times 100\%$$

for the n = 1 and n = 3 curves. For identical models the difference would be zero everywhere. In Fig. 13 the difference is greatest at the top and bottom

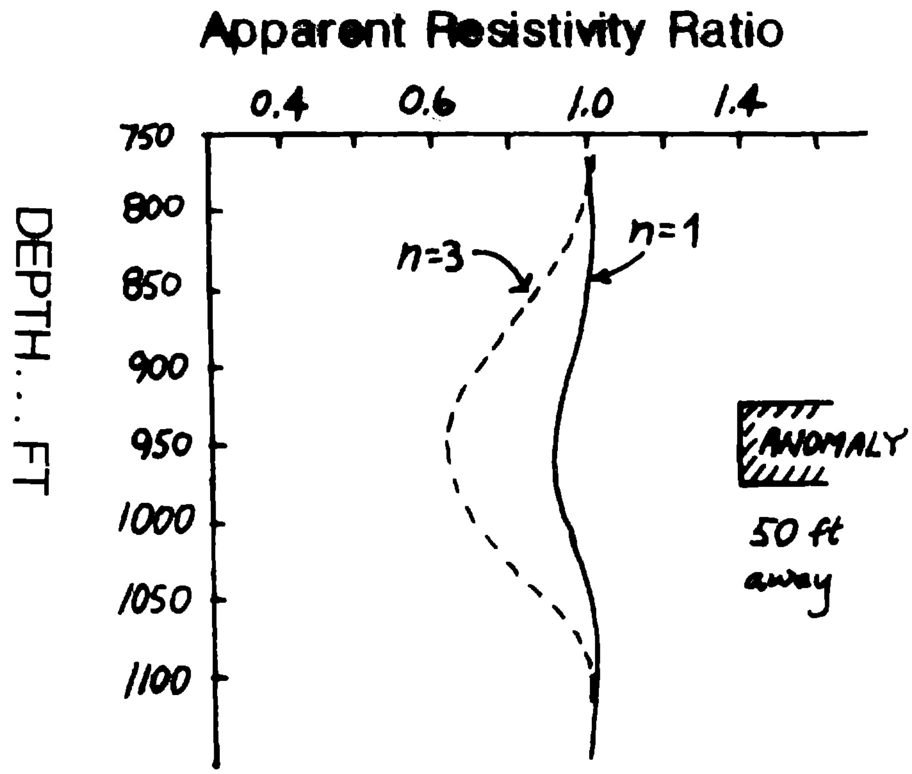

Figure 11. Ratio of the curve of Fig. 10b to the curve of Fig.10a versus depth in feet. The depth location of the anomaly in curve 10b is shown for reference.

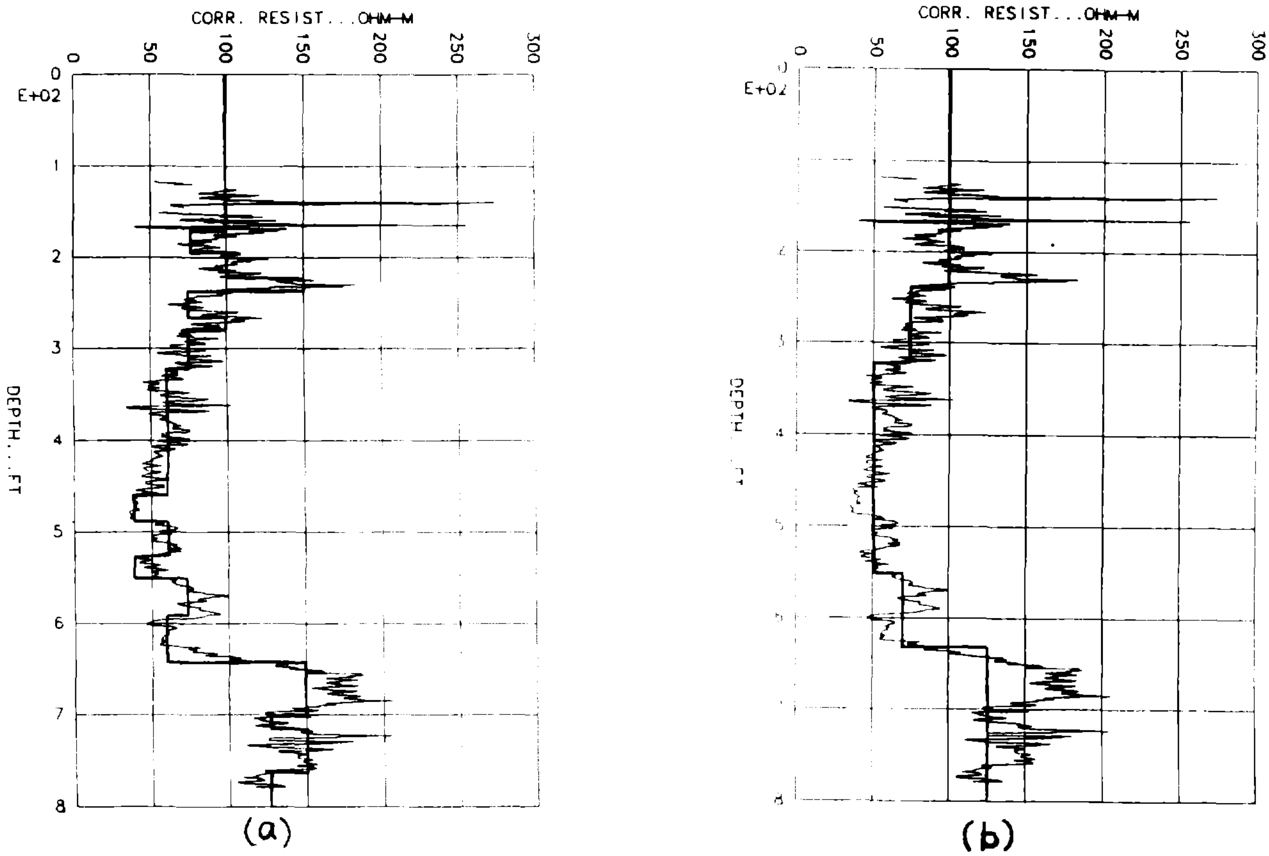

Figure 12. Fine (a) and coarse (b) layer models for the BHDH log of hole U4ac.

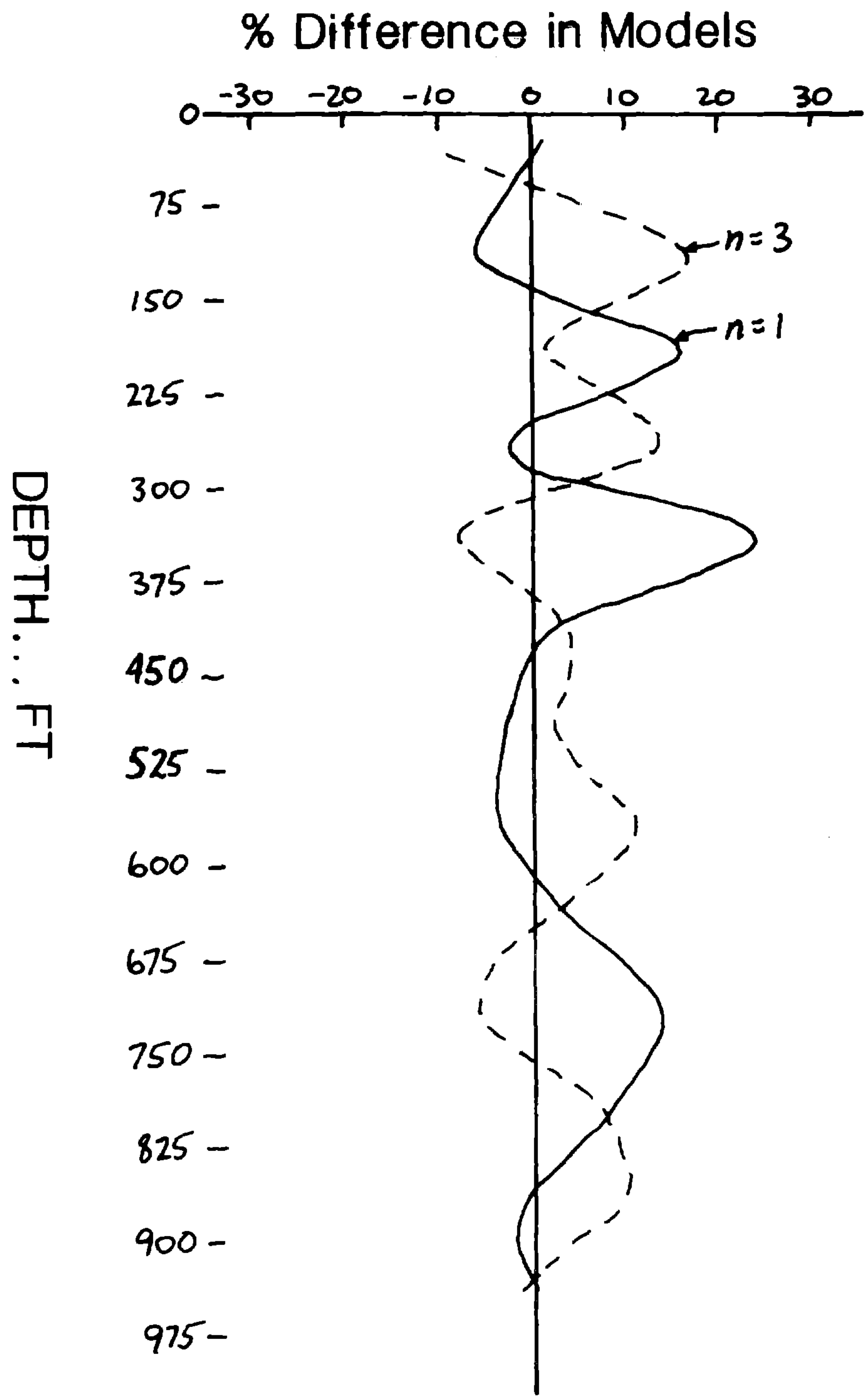

Figure 13. Ratio of the percent difference in calculated apparent resistivity for the structures of Fig. 12a and Fig. 12b, versus depth in feet.

of the log where changes in resistivity are most numerous and the model differences are greatest. In the central section the resistivity is less variable and the curves are more alike. The maximum difference in the curves is 24%, but in most places is less than 15% for both n = 1 and n = 3. The above comparison gives an estimate of the uncertainty involved when the electric log curve is modeled and used as a background reference curve when interpreting results of a hypothetical dipole-dipole downhole survey. Because of the variability between different model geometries which may be used, as illustrated in Fig. 13, background "noise" levels of 15 to 20% should be expected. In order to be reliably detected, then, an anomaly would have to have an apparent resistivity signature curve with an amplitude of more than 20%.

The true test of data interpretation is whether an interpreter can detect an anomaly when the "true" background model is not known. Such a situation was simulated by taking the BHDH log for U4ac and having each of the authors independently, in secret, develop his own model from the BHDH curves. In each case a low resistivity anomaly, to simulate a clay zone, was placed in the model and the RESIS2D code (Z-shift=0) used to calculate dipole-dipole response curves. The response curves were then exchanged, and each author attempted to detect the anomaly hidden within.

The procedure used by the interpreter in each case was to divide the curve given him by the background curve he developed from the BHDH log. This relative curve was then examined for signatures similar to those produced in Figures 4 to 8. When a signature representing a possible anomaly was found, the interpreter compared the curve with those of Figures 4 to 8 to try to estimate resistivity contrast, thickness, and distance of the anomaly from the borehole.

Figure 14 shows the result of one of the interpretive exercises. Fig. 14a shows the U4ac BHDH curve with an 8-layer resistivity structure chosen to represent the curve. A 5 ohm-m anomaly was placed between 390 and 510 ft, 57 ft (3/4a) from the borehole, for an average resistivity contrast of about 1:10. The interpreter chose to use the fine (17) layer model shown in Fig. 12a as the background reference. Results of dividing the output of the model (Fig. 14a) by the Fig. 12a model are shown in Fig. 14b. For n = 3 a 50% change is seen between 325 to 575 ft - a signature well above the ± 20% background. The interpreter used the curves of Fig. 14b to identify the anomaly as being less than 75 ft (one dipole length) from the borehole wall, with greater than 1:10 resistivity contrast, centered at a depth of 450 ft., and 150 ft. thick. This interpretation is in good agreement with the actual simulated anomaly. Note, however, that interpretation in this case was aided by the anomaly being located in a part of the curve where the background model was very similar to the simulated model as discussed in the case shown in Fig. 13.

Another interpretive exercise was run, again using the BHDH log for U4ac, where the anomaly was placed in a part of the borehole with greater resistivity variation. The simulated field case was generated using the 17 layer model of Fig. 12a with an anomaly of 5 ohm-m, 112.5 ft. thick (1 1/2 a), 112.5 ft. away from the borehole, centered at a depth of 225 ft. The simulation model and anomaly location are shown in Fig. 15a. The average resistivity contrast for the anomaly is about 1:17. The interpreter, without knowledge of the Fig. 15a model, chose to use the model of Fig. 14a (without the anomaly) as a background reference. Results of the RESIS2D calculations and division of the dipole-dipole response curves are shown in Fig. 15b. The

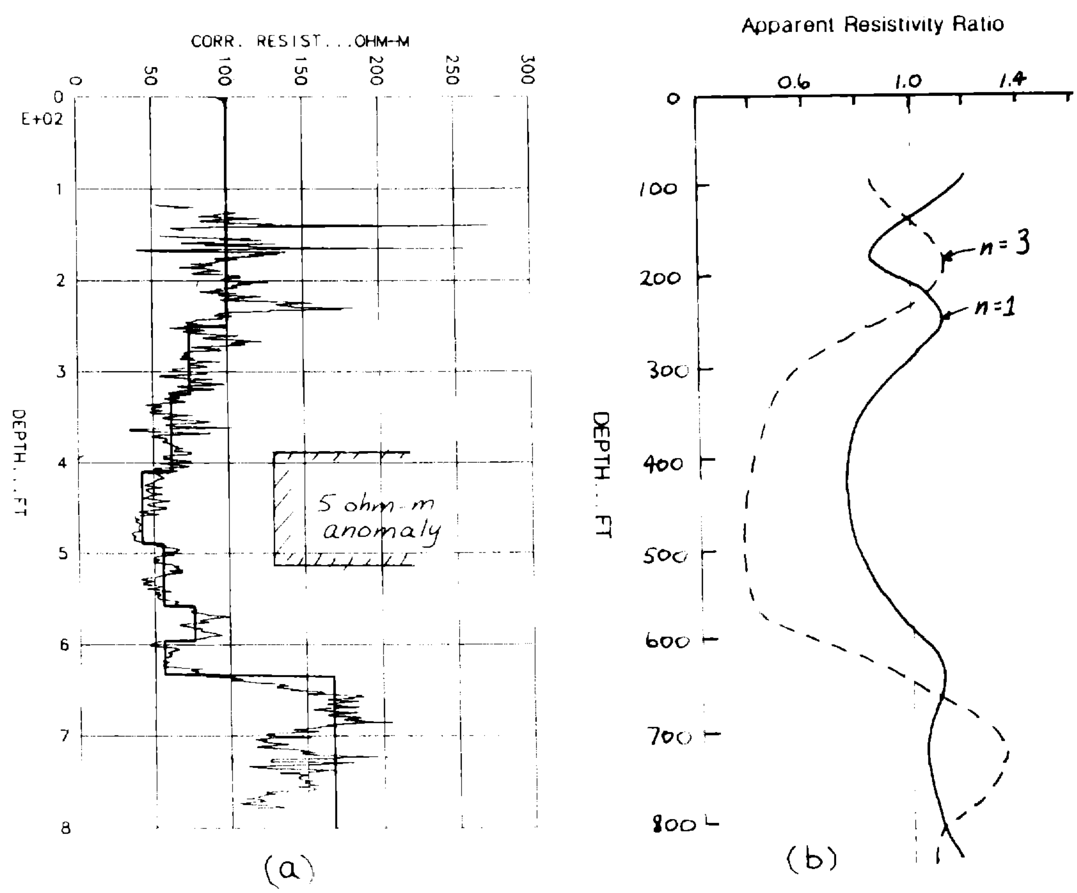

Figure 14. (a) BHDH log for U4ac and resistivity model with anomaly. (b) Ratio plot of (a) using the fine model curve of Fig. 12a as the background reference.

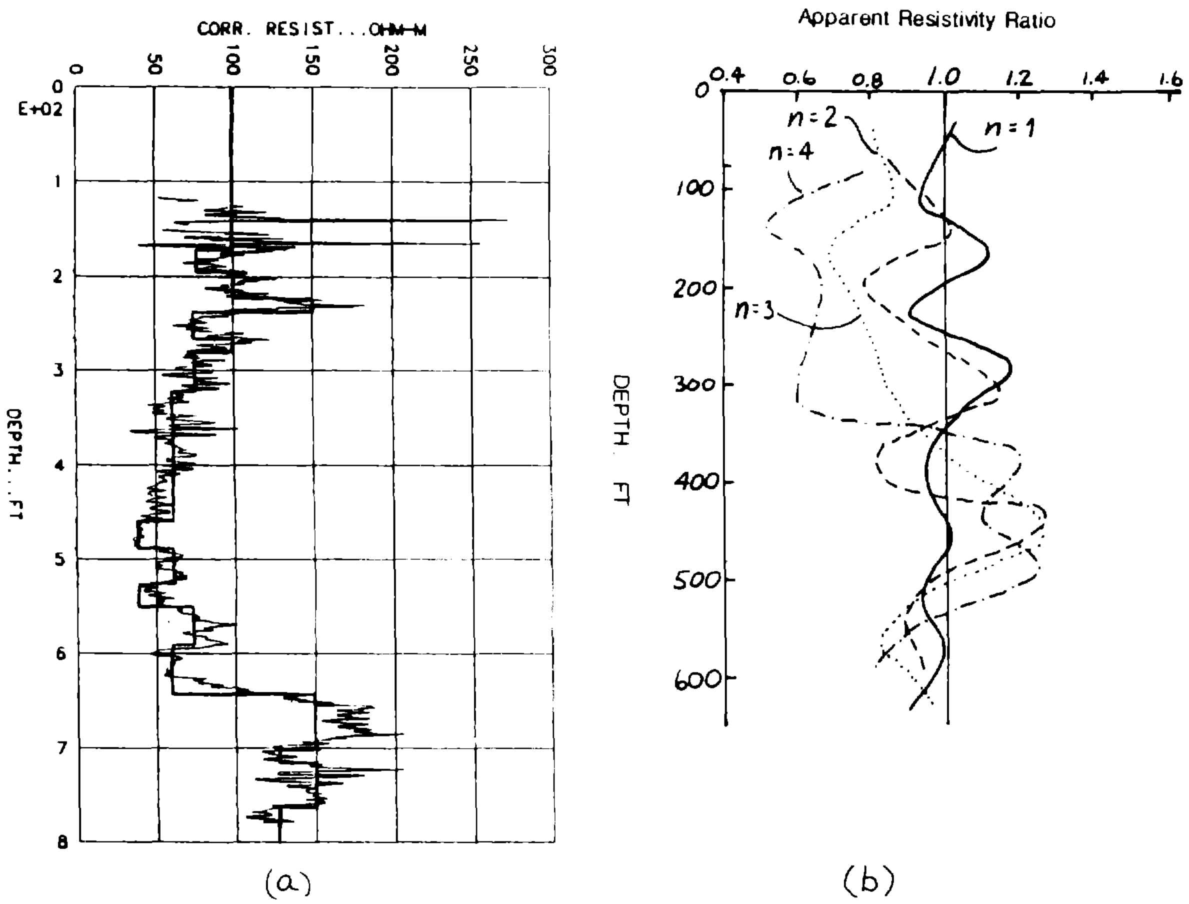

Figure 15. (a) BHDH log of U4ac with 17 layer simulated model and 5 ohm-m anomaly. (b) Plot of the dipole-dipole curves Fig. 15a divided by the interpreter's background model shown in Fig. 14a.

interpreter looked for responses in the curve representing deviations of more than 20%. For the n = 3 and n = 4 spacings there are anomaly peaks of 68% and 53% in the region between 75 and 300 ft. No peaks greater than 20% are observed for the n = 1 and n = 2 curves. This suggests that the anomaly represents a low resistivity zone located more than one dipole length, 75 ft., from the borehole. Using the curves of Fig. 4 to 8, the interpreter estimated an anomaly thickness of 2 dipole lengths - 150 ft., with a greater than 1:15 resistivity contrast. The anomaly was estimated to be centered at a depth of 225 ft. This interpretation is in good agreement with the true model.

Another test model was run using the coarse and fine resistivity structures of Fig. 12. Anomalies of 5 ohm-m were again used with resistivity contrasts of 1:14 and 1:20. The anomalies were one-half dipole length thick (1/2 a = 37.5 ft) and were placed 2a and 3 a (150 and 225 ft.) away from the borehole. In these cases the signature of the anomalies was well below the 20% detectable limit. From Figs. 4 to 8 it can be seen that with a 20% amplitude detection criterion anomalies located more than 1 1/2 dipole lengths from the borehole would be difficult to detect.

One may ask whether an anomaly can be detected merely by interpreting (modeling) a dipole-dipole tool response curve without the use of the BHDH log to generate a background model. This can be done by using the RESIS2D code iteratively in a "forward" modeling mode. In this case, a model is generated, the dipole-dipole response is calculated, and the results are then compared with field results. The model is modified until calculated and field results are in reasonable agreement. An interpretation exercise was devised to evaluate this technique.

The exercise was carried out by calculating a set of simulated dipole-dipole response curves based on an arbitrary resistivity structure containing an anomaly. The curves were then given to the interpreter who had no knowledge of the model used to generate them. The interpreter then used the RESIS2D code in the forward mode to interpret the data.

The simulated curve is shown in Fig. 16a. The interpreter's generated curve is shown in Fig. 16b. Iterations of the interpretation modeling were terminated after 8 runs of the code. The modeling effort could have been further refined with more runs. The agreement of the curves of Fig. 16 is very good below electrode locations 2 and 3. The fit is good for n = 1 along almost the whole curve, except for the section between the 0 and 1 electrodes. The n = 3 curve matches well everywhere except for the section at depths shallower than 4-5a.

The two models used to generate the curves of Fig. 16 are compared in Fig. 17. It can be seen that the anomaly centered near 7.5a depth was detected quite accurately, though its thickness was underestimated by 0.5a. The major difference in the models, however, is that the interpreter postulated another anomaly, 1a thick and 1.5 a from the borehole, at a depth of 5a. This anomaly was put in the model in an attempt to match the n = 3 curve. With no anomaly present, the background model shown resulted in high values for the n = 3 curve in the 4a to 5a depth range. This type of "false alarm" might well have been avoided in the case where an electric log was used to create a background model. The important thing to note here, however, is that interpretation of the curve did result in detection of a significant anomaly that would not have been seen with the electric log alone.

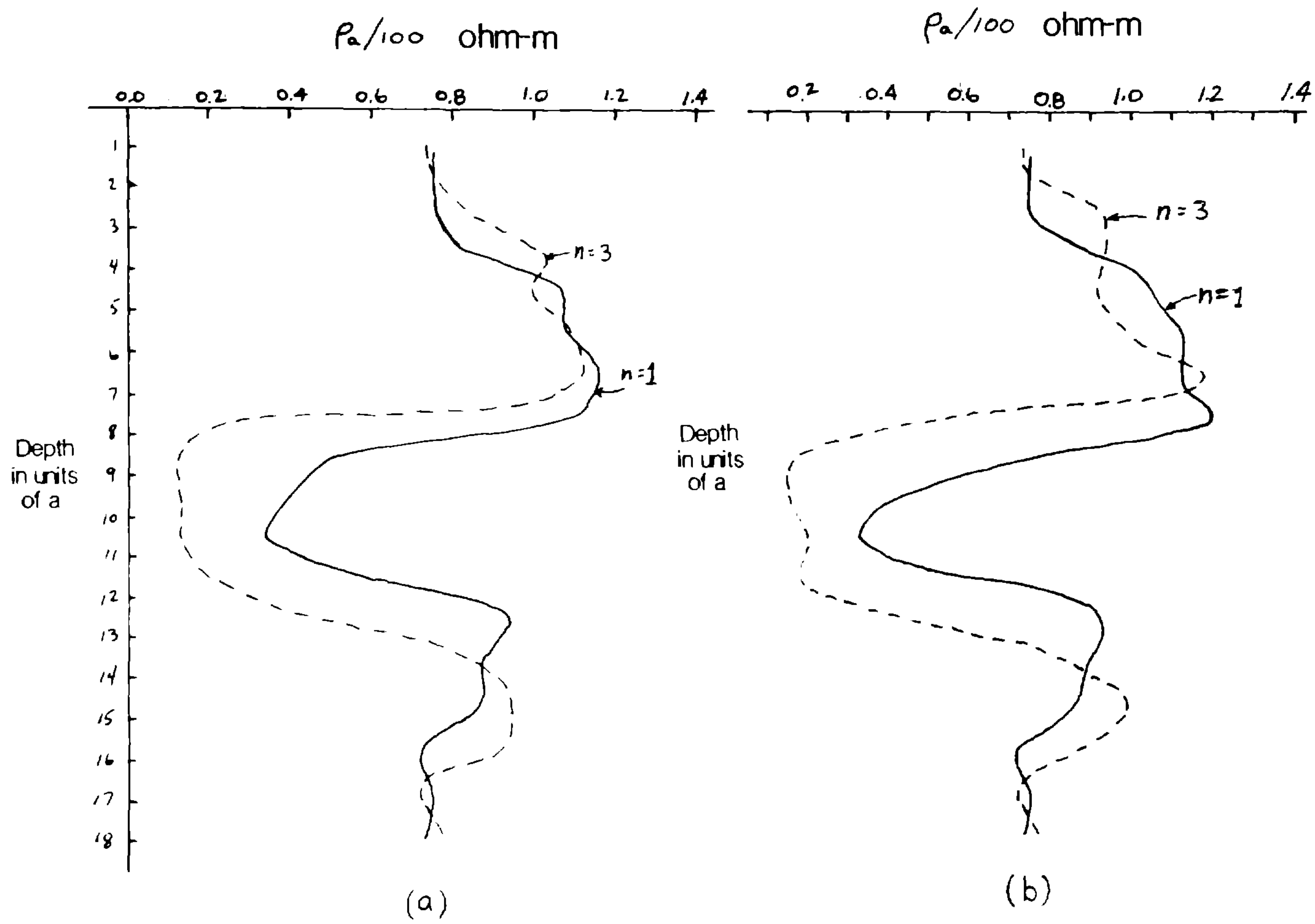

Figure 16. Simulated relative apparent resistivity curve (a) of a dipole-dipole apparent resistivity response in a borehole and the interpreter's curve (b) in an attempt to model curve (a).

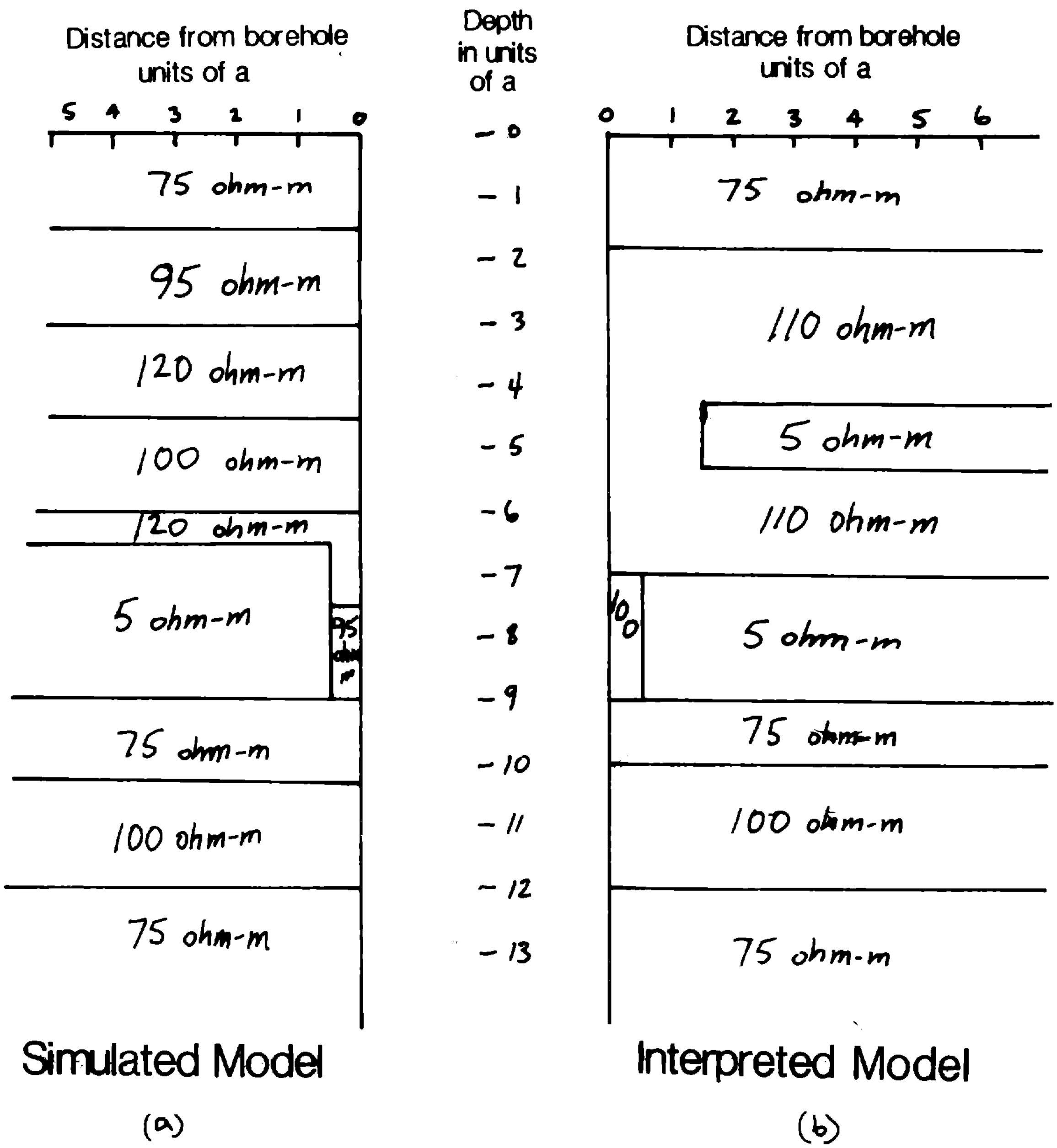

Figure 17. Resisitivity structures used for the simulated (a) and interpreted (b) model curves generated for Fig. 16.

IV. Summary and Recommendations

The modeling results demonstrate that a large-spacing downhole dipole-dipole tool offers significant improvements over surface methods for the detection and characterization of low resistivity clay zones. Ideally, the tool is best used in conjunction with the electric log. The electric log gives a good indication of the resistivity structure near the borehole which can be divided out as a background reference when interpreting the dipole-dipole results. The dipole-dipole data can provide useful results without the electric log data, but, as shown above, the possibility of false alarms is increased.

Field experience with surface dipole-dipole measurements indicates that data are repeatable within about 5-10%. A similar repeatability of electric log data is seen by comparison of separate runs of the electric log in the same hole. It was shown above that when the electric log curve is used as a reference in interpreting the dipole-dipole curves, differences of up to 20% are possible due to the uncertainty in the electric log model. This is a somewhat artificial difference - in the real case the difference will depend to a great extent on how well the electric log curve actually represents the true background. We feel that a conservative guideline to detect an anomaly is measurement of a response 20% above background. Using this 20% detection criterion, we can go back to Figs. 4 to 8 to get an estimate of tool performance.

The distance from the borehole at which an anomaly can be detected and the lateral resolution of the anomaly are dependent upon the dipole length used. The thickness of the anomaly affects the width of the anomaly response curve, while the response curve amplitude is affected by anomaly distance and resistivity contrast.

In Figure 18, curves are shown for an anomaly with resistivity contrast 1:5, 1 1/2 dipole units thick, and 1 and 2 dipole units from the borehole. Calculations were done, with a Z-shift of 3, for a whole-space approximation. The anomaly is almost detectable at the 20% level for n=2 when 1a away and would definitely be seen for n-spacings of 3 or more. When the anomaly is 2a away it makes only a 10% change in the profile even at n=4, and thus could only be detected in very ideal situations. Thus, we conclude that for detection:

- o For resistivity contrast 1:5 or greater:
    - anomaly more than one and one-half dipole length thick and anomaly less than one dipole length away

From an examination of Figs. 4a and 19, similar to the one done for Fig. 18, we conclude that an anomaly with 1:20 contrast must meet the following conditions for detection:

- o For resistivity contrast 1:20 or greater:
    - anomaly more than 1 dipole length thick, <u>and</u> less than one dipole length away
    - anomaly more than 2 dipole lengths thick, <u>and</u> less than two dipole lengths away

We expect 1:20 to be a typical resistivity contrast of montmorillonite clay in a tuff matrix in Yucca Flat. Thus a clay zone 20 m thick must be less than 20 m from the borehole, a 40 m thick clay zone less than 40 m away to be detectable, and so on. The limit of detected thickness and distance is the dipole length used in the tool that can be fielded in the borehole.

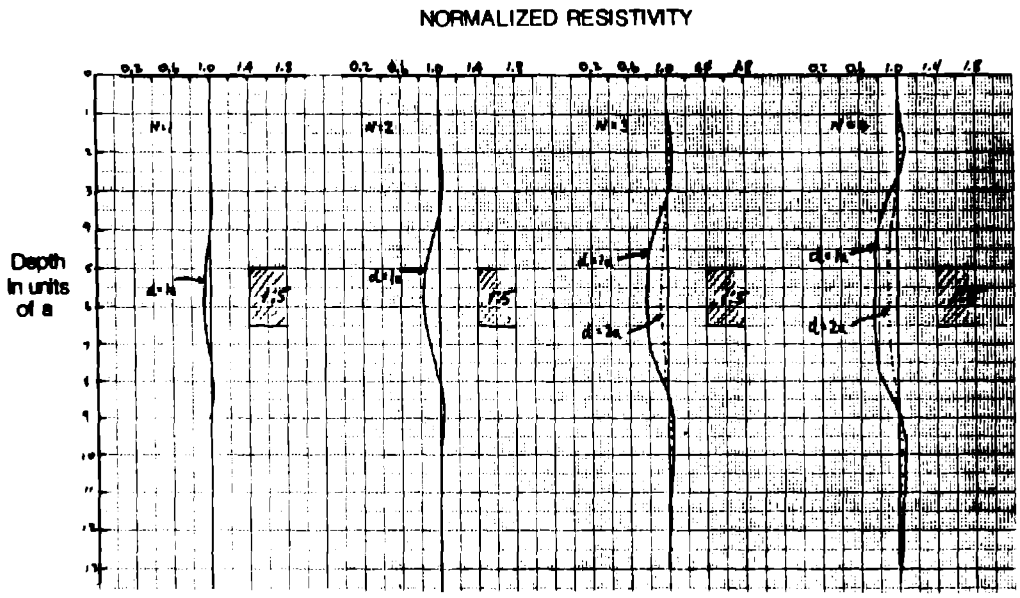

Figure 18. Whole-space approximate solution (Z-shift=3) of normalized apparent resistivity down a borehole. Anomaly is 1 1/2a thick with a resistivity contrast of 1:5.

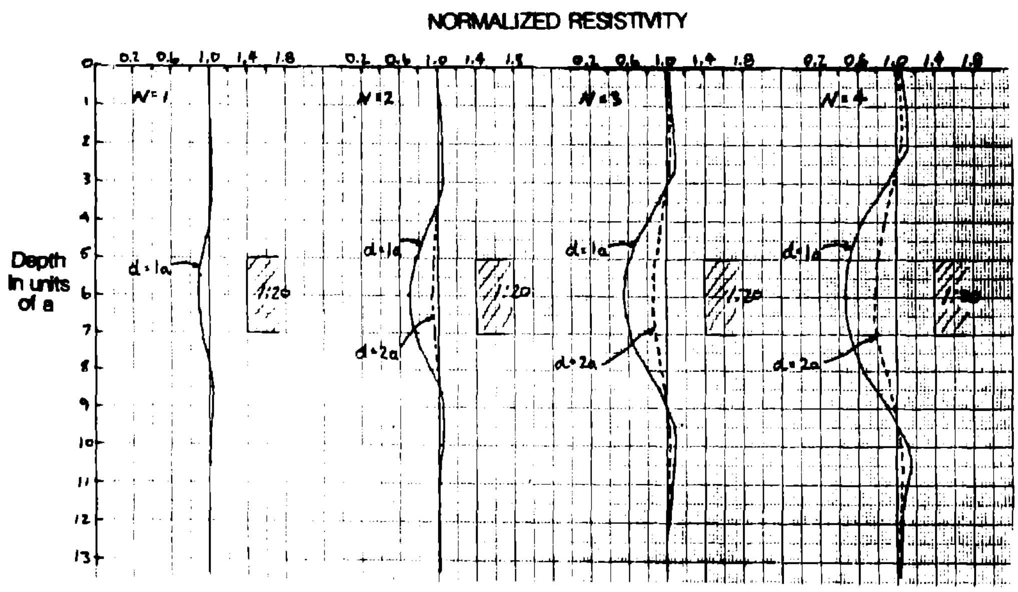

Figure 19. Whole-space approximate solution (Z-shift=3) of normalized apparent resistivity down a borehole. Anomaly is 2a thick with a resistivity contrast of 1:20.

The top of the anomaly must also be at least one dipole length above the bottom of the borehole to be detected. In practical terms, to ensure that a low resistivity clay zone is more than 40 m from a test shot working point, for example, the borehole must extend 40 m below the working point. For a distance of 100 m, the hole must extend 100 m below, and so on. The modeling shows that a detected anomaly can be unambiguously characterized in terms of depth from the surface, contrast, thickness, and distance from the borehole. These quantities can be determined from response curves from two or more runs at different dipole spacings. Additional runs using different dipole lengths at different spacing could further refine the interpretation. The interpretation exercises show that the depth from the surface and the distance of the anomaly from the borehole can be accurately determined under conditions expected to be encountered.

The following criteria would have to be met in order to carry out large-spacing downhole dipole-dipole surveys in a large diameter dry hole:

1/ an ability to string 4 electrode assemblies independently to vary dipole length by 5 to 40 m and dipole spacing by 5 to 160 m.

2/ ideally the tool would be operated in a continuous reading mode, i.e. continuous electrode contact - but a clamping scheme would be an acceptable alternative.

3/ provision to lead all power cables to the surface for interface with current source and voltmeter receiver.

The large-spacing dipole-dipole borehole tool will yield important information no other borehole tool can provide at present about deeply buried resistivity anomalies at large distances from the borehole. Our modeling indicates that the detection capability of such a tool is adequate to detect thick (> 40 m) clay zones within 40 m of a borehole. A further advantage is that this tool can be used in a surface-to-borehole mode (not evaluated here) which could be of great value for exploration of possible test areas. The authors recommend that serious consideration be made toward a development effort to field a large-spacing dipole-dipole big hole dry hole electric logging tool.

ACKNOWLEDGMENTS

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REFERENCES

Daniels, J. J., 1977, Three-dimensional resistivity and induced-polarization modeling using buried electrodes, Geophysics, Vol. 42, No. 5, pp. 1006-1019.

Dey, A. and Morrison, F., 1976, Resistivity Modeling for Arbitrarily Shaped Two Dimensional Structures, Lawrence Berkeley Lab. Tech. Rept. LBL-5223, 18 pp.

Keller, G. V., and Frischknecht, F. C., 1966, Electrical Methods in Geophysical Prospecting, Pergamon Press, 523 pp.

Lytle, R. J., 1984, The Influence of the Ground Contacting System On Cross-Borehole and Borehole-To-Surface Electrical Measurements, Lawrence Livermore National Laboratory report UCRL-90932.

Lytle, R. J. and Hanson, J. M., 1983, Electrode configuration influence on resistivity measurements about a spherical anomaly, Geophysics, Vol. 48, No. 8 pp. 1113-1119.

Olsen, C. W., 1983, LLNL Site Selection Procedures, Lawrence Livermore National Laboratory Tech. Rept. UCRL-89416, 12 pp.